AN APPROACH TO THE OPTIMAL LOCATION OF MODULES IN A MARINE SYSTEM WITH RESPECT TO ITS UNSCHEDULED DOWNTIME

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by

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ABSTRACT

The accessibility of a constrained system consisting of box-shaped modules within an arbitrary box-shaped boundary with one, single access opening is investigated in general and more specifically for the case of marine systems.

The objective is a minimization of the total length of the expected time periods required for moving failed modules, one at a time, to the access opening and back to their original positions in the system.

An algorithmic method is proposed for a computer aided approximation of the optimal allocation of the modules in the system in view of unscheduled downtime. The total of the module volumes is smaller than the total volumes within the system's physical boundary. The modules may have constraints with respect to their absolute and relative positions in the system.

Thesis Supervisor: Professor S. A. Coons

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NOMENCLATURE

Symbol	Meaning
$R(t)$	Reliability
$M(t)$	Maintainibility
F_{acces}	Accessibility
$\lambda(t)$	Instant failure rate
T_i	Meantime to replace
λ	Exponential instant failure rate
t,	Time
i	Rank of module
$E(\ )$	Expected value of ( )
t_r	Repair time
x_i	Distance of center of gravity to y-axis
y_i	Distance of center of gravity to x-axis
x_w	Width of module
y_h	Height of module
x_r	Minimum service access distance
x_l	" " " "
y_t	" " " "
y_b	" " " "
x_B	Width of boundary
y_D	Height of boundary
MAX[ ]	Maximum value of [ ]
MIN[ ]	Minimum value of [ ]

INTRODUCTION

One of the major system effectiveness parameters for marine systems is the availability of the system for its mission.

Availability is defined here as being the expected fraction of the time between scheduled overhauls, that the system will be operational within certain tolerances and under specified environmental conditions. So the availability depends on the frequency of the occurrence of failures of the system and the time required to bring the system back into its operational state. Hence the reliability of the subsystems, that force the whole system into the downstate, as well as their repair time is crucial for the contribution of the availability to the overall system effectiveness. With the systems downstate is meant the abandonment of the systems mission.

Reliability and maintainability are studied to great extend over the last decade, [1], [2], [3], mainly for its importance mentioned above. Some examples of the application of reliability and maintainability theory are

--required redundancy

--trade off of system component reliability with respect to cost of improved reliability

--preventive maintenance

[illegible]

The reliability and maintainability concepts, which are used in this paper will be defined later.

The application of reliability and maintainability theory is one of the factors that did trigger the introduction of "packaged" units. A development that started in the electronic industry during the fifties and found its way into practically all engineering fields. "Packaged" subsystem units are physically self-contained functional subsystems. The advantage of the use of such subsystems is that they can be removed and replaced as single units with a "plug in -- unplug" type of operation. In case of failure during active mission time (unscheduled failure) the repair time will be sharply reduced, due to the avoidance of cumbersome inspection, take apart and put together methods, which is most of the time the consequence of the lack of sufficient working space and lack of proper tools.

Electronic systems are modularised extensively at present. The multitude of standard basic circuits in practically every system as well as the miniaturization tendency contributed much to the modularization. The implementation of the module idea caused a steady increase of the availability of electronic systems.

[illegible]

The modulation of mechanical systems, specifically the ones in the marine field are handicapped presently by weight, volume, accessibility, physical connections to the rest of the system and by the wide variety of shapes and dimensions of system components. Miniaturization, however, of marine subsystems as for example the increasing application of marine gas turbines and high speed diesel engines for main propulsion and power generation does open more and more possibilities for "packaged" units. And with this introduction, the importance of accessibility increased in order to utilize fully the advantage of packaging of subsystems.

The availability, as defined above, depends on, in addition to the frequency of failure:

1. Time required to remove the failed module from the system and transport it to the access opening of the systems boundary.
2. Waiting time for the arrival of a new or repaired module.
3. Time required to transport the new module from the access opening to the original location of the removed failed module and to reinstall it.

[illegible]

The time under point 2 is a pure logistic problem, which is covered frequently in the operations research literature. It is assumed to be fully independent of the time periods under points 1 and 3. The removal and reinstallation times depend, of course, on the way that a module is connected to the system. The time necessary to transport a module through the system to the access opening depends mainly on its design location and the number of obstacles, with their removal times, that have to be displaced.

It is this last topic which has our special interest.

Systems Accessibility

The replacement of modules in a marine system is often complicated by the limitation of volume within its water tight, permanent structural enclosure. Modules, ladders, pipes, wires, and structural members such as pillars, web-frames, etc., form serious obstacles for the replacement of a failed module. The typical example is the engine room of a conventional ship. In general, only one single access opening is provided.*

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*In some cases access is provided by removing parts of the structural enclosure. This method has its disadvantages and will not be considered in this study.

The importance of volume for payload in many ships plays a role in this limitation of non-payload spaces. Specifically in the so called "volume limited" ships, such as destroyers, container ships, etc., these spaces are compressed. The degree of compression is governed by the cost for operation of the subsystems within these compressed volumes and the increase of system effectiveness due to extra payload volume.

The displacements and removals of other modules, piping and wiring in order to make the way free for a failed module requires, in most cases, a more than considerable fraction of the total unscheduled systems downtime. It is known that unscheduled downtime represents extremely high losses for the systems owner. This led already, as mentioned above, to the module concept, but also stresses the problem of providing as much physical "free way" as possible for expected failures.

A module has an expected required time for disconnection and connection to the system, which is known for each specific module. Also known is the expected number of failures for each "critical" module. With "critical" is meant that each "critical" failure causes the whole system to fail. So we are able to predict the frequency that the whole system will be down due to failure of each specific module and the frequency that

each module will be transported through the system. This brings us to allocate modules in such a way that the expected time necessary to transport all modules weighted by their failure rate is minimized.

The present design method of allocating modules in volume constrained marine systems are:

1. Copy existing design and improve manually. By which is meant trial and error. This is not very successful as a consequence of the extreme complexity. Geometrical accessibility is criterium for improvement. Reliability and maintainability are only considered intuitively. No quantitative method is known.
2. Computer aided "light pen" design method. This method takes only in account the geometrical accessibility, but provides many more trials and hence probability of improvement than the first method does.

Defining the Thesis Objective

The purpose of this thesis is:

1. To quantify the accessibility of a given system by construction of an explicit objective function and its constraints, specifically in view of

volume limited marine systems. The accessibility is considered with respect to the total replacement of a single failed module which causes unscheduled downtime.

2. An approach to the determination of the optimal allocation of the subsystem modules during the design stage of the system, minimizing the objective function of the accessibility with its constraints.

Accessibility Measurement

Systems With Perfect Accessibility

As stated in the introduction, we are interested in the unscheduled downtime of the whole system caused by the time to remove and replace one single module from the system. Before looking into the accessibility of a volume constrained system, we will first consider one which is assumed to be perfectly accessible, i.e., there are no obstacles whatsoever that would delay the replacement of a failed module, other than the total time required for

--operation of disconnecting the failed module.

--to lift the module from its location.

--operation of reinstalling a new or repaired module.

The expected downtime of each module is in this case only determined by the reliability and the repair time characteristic for the module. No geometrical constraints would have an influence.

A few basic principles of the reliability theory will be reviewed in the following pages, such as the accessibility, as approached in this study, depends on it. The reliability, R(t), of a module is defined as the probability that a module will retain its operating characteristics longer than a certain time under given environmental conditions.

So,

$$R(t) = P(t_1 > t) \tag{1}$$

where the random variable, t_1, presents the time to failure. The maintainability, $M(t)$, is here defined as the probability that the time required for the replacement operation of a given module or system of modules lasts longer than a certain time, using standard work methods. So,

$$M(t) = P(t_r < t) \tag{2}$$

where t_r is the time to repair.

The conditional probability for a specific module is P(failure in interval Δt from t to $t + \Delta t$ | given no failure up to t) = $\lambda(t)\Delta t$. The reliability of that module over the time period $(t + \Delta t)$ is, using (1):

$$R(t + \Delta t) = R(t)\ (1 - \lambda(t)\Delta t) \tag{3}$$

assuming that the failures of successive modules are independent.* For (3) one can write

$$\frac{R(t + \Delta t) - R(t)}{R(t)\,\Delta t} = -\lambda(t) \tag{4}$$

or write $\Delta t \rightarrow 0$,

$$\frac{R'(t)}{R(t)} = -\lambda(t) \tag{5}$$

Integration of (5),

$$\ln R(t) = -\int_0^t \lambda(t)\, dt \tag{6}$$

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*Which does not have to be true in the case of insufficient detection of the cause of failure.

as $R(o) = 1$, we obtain,

$$R(t) = e^{-\int_o^t \lambda(t)dt} \qquad (7)$$

$\lambda(t)$ represents the so called failure ratio of a module, which is the relative frequency of failure over a time interval $(t, t + \Delta t)$. The failure ratio is related to the reliability of a component in (7).

The sum of the total expected downtimes caused by each module per unit operating time will provide the expected systems downtime F_s. The distribution of the systems downtime can be derived, using [4], as follows from the probability density functions for the replacement times of each component $f_{t_r}(t_{r_o})$ and the probability mass functions of the number of failures over operating time $p_m(m_o)$. The p.d.f. of the total downtime t_s for a module is

$$f_{t_s}(t_{so}) = \sum_{mo} p_m(m_o)\, f_{t_s|m}(t_{so} | m_o) \qquad (8)$$

The number of failures and the replacement times are supposed to be statistically independent.

Taking the exponential (or s) transform

$$f^T_{t_s}(s) = \int_{-\infty}^{+\infty} e^{-st_s} \sum_{m_o} p_m(m_o)\, f_{t_s}(t_{so} | m_o)\, dt_{so}$$

$$= \sum_{m_o} p_m(m_o) \int_{-\infty}^{\infty} e^{-st_{so}} f_{t_s | m}(t_{so} | m_o)\, dt_{so}$$

$$= \sum_{m_o} p_m(m_o)\, [f^T_{t_r}(s)]^{m_o} \qquad (9)$$

where $[f^T_{t_r}(s)]^{m_o}$ is the s transform of $f_{t_s|m}(t_{so}|\, m_o)$. Equation (9) represents the discrete (or z) transform of the p.m.f. $p_m(m_o)$ with $z = f^T_{t_r}(s)$. Hence

$$f^T_{t_s}(s) = p^T_m\, [f^T_{t_r}(s)] \tag{10}$$

The expected value of $f_{t_s}(t_s)$ follows from differentiating (10) with respect to s

$$\left.\frac{df_{t_s}(s)}{ds}\right|_{s=0} \tag{11}$$

or

$$E(t_s) = -\left.\frac{dp^T_m\, [f^T_{t_r}(s)]}{d[f_{t_r}(s)]} \cdot \frac{d\, f^T_{t_r}(s)}{ds}\right|_{s=0}$$

$$= E(m)\; E(t_r) \tag{12}$$

In order to simplify we assume the number of failures to be Poisson distributed

$$p_m(m_o) = \frac{(\lambda t)^{m_o}\, e^{-\lambda t}}{m_o!}$$

The expected arrival rate of failures E(m) is in this case constant and equal to the failure rate (t).

$$E(m) = \lambda_i(t) = \lambda_i = \text{constant} \tag{13}$$

The index stands for the rank of the systems module.

The acceptance of a constant failure rate for mechanical systems is only more or less true, but is in reliability studies of such systems common practice.

An expected value of the repair time will be known in general from $f_{t_r}(t_r)$.

$$E_i(t_r) = T_i \tag{14}$$

So we obtain a simple expression for the expected total replacement time of each system component per unit operating time

$$E_i(t_s) = \lambda_i T_i \tag{15}$$

The expected downtime F_s of the overall system per unit of operating time is the sum of the expected individual module times. So

$$F_s = \sum_{i=1}^{n} E_i(t_s) = \sum_{i=1}^{n} \lambda_i T_i \tag{16}$$

where i = rank of module.

n = total number of modules in system.

The equation (16) is valid for:

1. Perfect accessibility.
2. Independence of failures in successively replaced modules.
3. Constant failure rates.
4. Failure of each module i causes the system to be in the downstate.
5. No interactions between the modules.

Systems With Limited Accessibility

When a system is enclosed by a physical permanent boundary with only one single access opening, as described in the introduction, the availability of free space necessary for the removal and replacement of components will be present in marine systems. The "open" space limitations will make it necessary to remove, displace, and reinstall several other system components before a failed module, which is not located next to the opening in the boundary, can be replaced with a working one. For a marine system these obstacles will consist mainly of

--other modules

--piping and wiring

--structural numbers.

These system items do increase the replacement time with a vast amount in a "stuffed" engine room.

The optimal path for a failed system item to and from the access opening will be the one with a minimum of replacement time. With replacement time of a failed module is meant the time required for:

--disconnecting,

--displacing, and

--reinstalling

of all modules that are effected by the operation. Now we make the assumption that the transport time of a module

through "free" space is negligible compared to the time necessary for disconnection, etc. in order to provide a free path. This assumption approximates certainly the reality in present marine systems, but will become invalid if the individual module replacement time approaches zero.

By taking into account all the assumptions, the total replacement time for a failed module is

$$T_{t_i} = T_i + \sum_{\alpha_i} T_j \qquad (17)$$

where α_i = the set of modules that should be displaced in order to provide access for replacement of module i.

T_i = time to disconnect and reinstall module i <u>at its location</u> in the system.

In (17), the possibility neglected is that modules are connected in such a way that removal of one reduces the replacement time of another subsystem.

Due to the fact that we limit ourselves to unscheduled downtime, we only consider the removal and replacement of one single module at a time. In this case, the systems downtime function is, by replacing T_i in (16) with T_{t_i} in (17). So

$$F = \sum_{i=1}^{n} \lambda_i (T_i + \sum_{\alpha_i} T_j) \qquad (18)$$

or

$$F = \sum_{i=1}^{n} \lambda_i T_i + \sum_{i=1}^{n} \lambda_i \sum_{\alpha_i} T_j \tag{19}$$

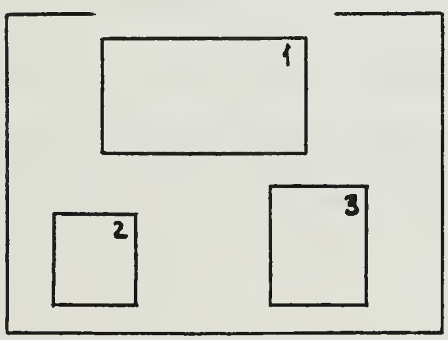
The failure rate λ_i and the replacement time T_j are known and given. Hence the first term in (19) represents a constant. The cross terms in (19) represent the expected time required for moving the modules through the system to the opening and back. Its minimum value is hence a measure for the accessibility of this system. The objective function by which the accessibility is quantitatively measured is by leaving out the constant term in (19).

$$F_{acces} = \mathrm{MIN}\left[\sum_{i=1}^{n} \lambda_i \sum_{\alpha_i} T_j\right] \tag{20}$$

Minimization of (20) during the systems design phase leads to maximization of the accessibility.

Two 2-dimensioned examples of three component systems show the application of (20).

EXAMPLE 1



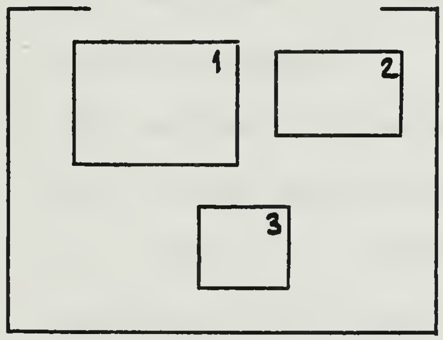
The numbers represent the module ranks.

Figure 1

In order to take out module 2, as well as module 3, number 1 has to be displaced. Hence

$$F_{acces} = \lambda_2 T_1 + \lambda_3 T_1$$

<u>EXAMPLE 2</u>



$T_1 > T_2$

<u>Figure 2</u>

In this case only one of the modules, 1 or 2, has to be displaced in order to provide free way to module 3. Given $T_1 > T_2$ implies

$$F_{acces} = \lambda_3 T_2$$

In practically no system, specifically not marine systems, does one have complete freedom of allocation during the design phase with respect to maximum accessibility in a given volume.

Constraints for each module are present and are in general:

1. <u>Absolute geometrical constraints</u>
   a. Zero degrees of freedom. Position fixed with respect to the permanent boundary. For example, the propulsion unit on the propeller shaft.
   b. One degree of freedom, e.g., propulsion unit along centerline of propeller shaft.
   c. Two degrees of freedom, e.g., auxiliary generators at bottom of box for reasons of supports.
   d. Three degrees of freedom. Module can be anywhere within the permanent system boundary.
2. <u>Relative geometrical constraints</u>
   a. Minimum required service access which is mostly given for each subsystem as well as known from experience [5]. The same service space can be shared in general by several systems in which case the maximum values determine the minimum mutual distances of the modules.

b. Maximum mutual distances of modules. This might be a design requirement to limit piping and/or wiring between two modules.

Module Allocation with Respect to Accessibility

General

This chapter will deal with the design aspects and method of allocating modules in a given volume in such a way that the accessibility is optimal with respect to the objective function derived in the last chapter.

The minimization of

$$F_{acces} = \text{MIN} \left[\sum_{i=1}^{n} \lambda_i \sum_{\alpha_i} T_j \right]$$

is required, while taking into account the geometrical constraints. So we have to determine the optimal set of the sets α_i. The sets α_i are interdependent, due to the existing geometrical relations of the modules in a constrained volume.

The objective function can only be minimized by the removal and the optimal combination of the terms $\lambda_i T_j$. No similar optimisation problem was found in the literature.

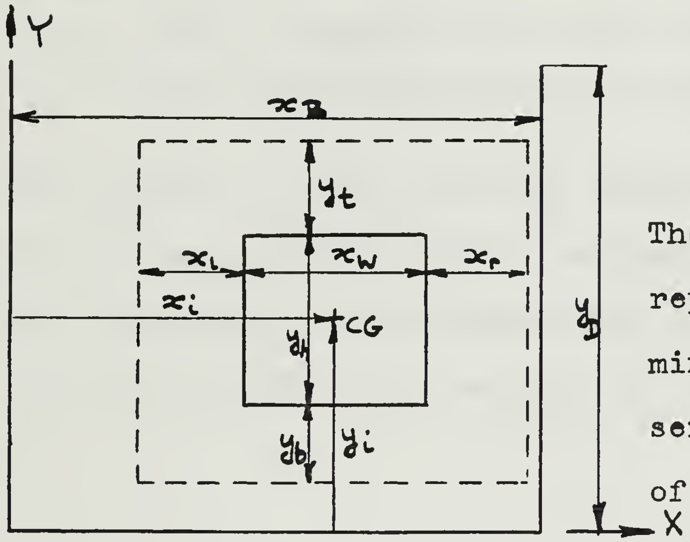
One way of solving this problem, and which is followed here, is the development of simple accessibility problems in two dimensions, only with a few blocs into more complicated ones and ending up, for so far as possible, with the general case with n modules in three dimensions.

In each case all possible configurations will be investigated. In order to simplify the problem somewhat, but keeping it realistic, the following assumptions are made:

1. The presence of piping and wiring is neglected. This is more or less reasonable as piping as well as wiring is more or less "flexible". After the modules are allocated, piping and wiring can be installed in such a way that it does not affect any module access route to and from the module locations. Moreover, the replacement of piping and wiring in case of unscheduled failures is in general a minor operation, as far as the overall accessibility is concerned (not at the location of repair itself). Wiring and piping pieces are relatively small and can be moved to and from the location of failure through the service access areas of the modules.

2. The presence of permanent structural members in the two-dimensional case is neglected. In the three dimensions are the members assumed to be modules with an infinite replacement time. The permanent boundary that surrounds the access opening can also be thought of as box-shaped modules with infinite replacement time and geometrical constrained in such a way that just the access opening is left open.

3. All modules as well as their minimum service areas and the boundary are assumed to have a box shape. Modules are not rotated during removal. An example of such a module in two dimensions is shown in Figure 3, as well as the nomenclature of the geometrical variables that are used in the next chapters.



The broken line represents the minimum required service access of the module.

Figure 3

In Figure 3 the index i indicates the rank of the module. Moreover,

x_i = distance of center of gravity to Y-axis.

y_i = distance of center of gravity to X-axis.

x_w = width of module (in x-direction)

y_h = height of module (in y-direction)

The minimum service access distances are represented by:

x_r = distance on right side of module

x = distance on left side of module

y_t = distance on top of module

y_b = distance on bottom of module

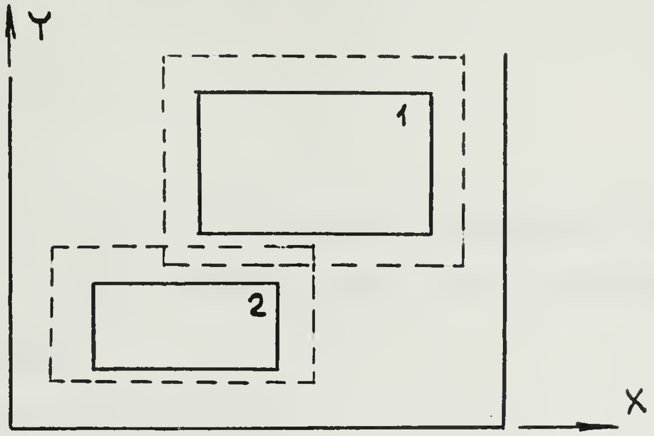
Boundary charactistics are:

x_B = width of boundary in x-direction

y_D = height of boundary in y-direction

So the objective of the following sections is the determination of the regions in which each module is allowed to be allocated with an optimal overall accessibility, while taking into account the assumptions made above.

<u>The Two-Dimensional Case With Two Blocs</u>



<u>Figure 4</u>

Constraints for the given configuration:

$$x_1 + \tfrac{1}{2}x_{w_1} + x_{r_1} \leq x_B \qquad (20A)$$

$$x_1 - \tfrac{1}{2}x_{w_1} - x_{l_1} \geq 0 \qquad (20B)$$

$$x_2 + \tfrac{1}{2}x_{w_2} + x_{r_2} \leq x_B \qquad (21A)$$

$$x_2 - \tfrac{1}{2}x_{w_2} - x_{r_2} \geq 0 \qquad (21B)$$

$$x_1, x_2 \geq 0 \qquad (22)$$

$$y_1 + \tfrac{1}{2}y_{h_1} + y_{t_1} \leq y_D \qquad (23)$$

$$(y_1 - \tfrac{1}{2}y_{h_1}) - (y_2 + \tfrac{1}{2}y_{h_2}) \geq \text{MAX}\,(y_{t_2}, y_{b_1}) \qquad (24)$$

$$y_2 - \tfrac{1}{2}y_{h_2} - y_{b_2} \geq 0 \tag{25}$$

$$y_1, y_2 \geq 0 \tag{26}$$

Free access for module 2, i.e., no temporary displacement of 1 in order to make the way free for 2 and hence $F_{acces} = 0$, when

$$x_1 - \tfrac{1}{2}x_{w_1} > x_{w_2} \tag{27}$$

$$x_B - (x_1 + \tfrac{1}{2}x_{w_1}) > x_{w_2} \tag{28}$$

From (20), (27), and (28);

$$x_1 > \mathrm{MAX}\ [(x_{w_2} + \tfrac{1}{2}x_{w_1}), (\tfrac{1}{2}x_{w_1} + x_{l_1})] \tag{29A}$$

and/or

$$x_1 < \mathrm{MIN}\ [(x_B - \tfrac{1}{2}x_{w_1} - x_{r_1}), (x_B - \tfrac{1}{2}x_{w_1} - x_{w_2})] \tag{29B}$$

or in a different form,

$$x_1 > \mathrm{MAX}\ [x_{w_2}, x_{l_1}] + \tfrac{1}{2}x_{w_1} \tag{30A}$$

or

$$x_1 < x_B - \tfrac{1}{2}x_{w_1} - \mathrm{MAX}\ (x_{r_1}, x_{w_2}) \tag{30B}$$

If the inequality (30) is not satisfied, free access for module 2 does not exist and the accessibility is

$$F_{acces} = \lambda_2 T_1 \tag{31}$$

In order to investigate if $F_{acces} \neq 0$, whether a reduction of the accessibility is possible or not, we must change the configuration by interchanging the modules 1 and 2.

Before making the interchange however, the conditions under which an interchange is allowed are to be known. The minimum service access distances on top and bottom of the modules may prevent an interchange, as the total height might be greater than the height of the box. These conditions are obtained by simply interchanging the indices in the constraints (20), (21), (22), (23), (24), (25), and (26). If the constraints with interchanged indices are met, the interchange is permitted.

Now make the interchange by interchanging the indices in the condition (30) for free passage.

$$x_2 > \mathrm{MAX}\ [x_{w_1},\ x_{l_2}] + \tfrac{1}{2}x_{w_2} \tag{30'A}$$

or

$$x_1 < x_B - \tfrac{1}{2}x_{w_2} - \mathrm{MAX}\ (x_{r_2},\ x_{w_1}) \tag{30'B}$$

Analogous to the original case, if the condition (30') is not satisfied,

$$F'_{acces} = \lambda_1 T_2 \tag{32}$$

Minimizing F_{acces} is possible only when:

1. Maintaining the original configuration from (30):

$$x_B - \text{MAX}\,[x_{r_1}, x_{w_2}] > \text{MAX}\,[x_{w_2}, x_{l_1}] + x_{w_1} \qquad (33)$$

2. Changing the configuration:

$$x_B - \text{MAX}\,[x_{r_2}, x_{w_1}] > \text{MAX}\,[x_{w_1}, x_{l_2}] + x_{w_2} \qquad (34)$$

or if (34) is not true

$$\lambda_1 T_2 < \lambda_2 T_1 \qquad (35)$$

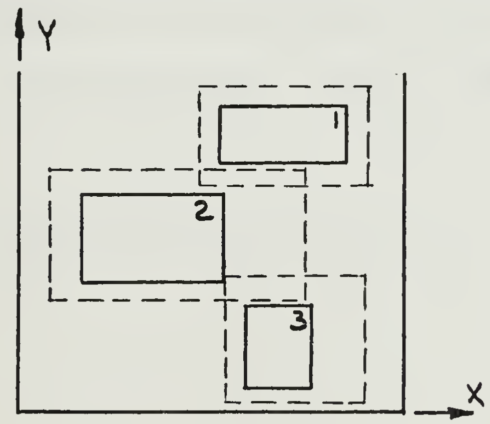
Summarising the optimisation procedure of the accessibility for the given configuration:

--Determine F_{acces} with (33).

--If $F_{acces} \nleq 0$ and the constraints (20) to (26) allow an interchange, interchange the modules. Determine F'_{acces}.

--If $F'_{acces} \angle F_{acces}$, the new configuration is determined by (20) to (26) with indices interchanged.

<u>The Two-Dimensional Case With Three Blocs</u> (A)



$y_1 > y_2 > y_3$

<u>Figure 5</u>

The configuration is determined in the x-direction:

$$x_1 + \tfrac{1}{2}x_{w_1} + x_{r_1} \leq x_B \qquad (36A)$$

$$x_1 - \tfrac{1}{2}x_{w_1} - x_{l_1} \geq 0 \qquad (36B)$$

$$x_2 + \tfrac{1}{2}x_{w_2} + x_{r_2} \leq x_B \qquad (37A)$$

$$x_2 - \tfrac{1}{2}x_{w_2} - x_{l_2} \geq 0 \qquad (37B)$$

$$x_3 + \tfrac{1}{2}x_{w_3} + x_{r_3} \leq x_B \qquad (38A)$$

$$x_3 - \tfrac{1}{2}x_{w_3} - x_{l_3} \geq 0 \qquad (38B)$$

in the y-direction by;

$$y_1 + \tfrac{1}{2}y_{h_1} + y_{t_1} \leq y_D \qquad (39)$$

$$(y_1 - \tfrac{1}{2}y_{h_1}) - (y_3 - \tfrac{1}{2}y_{h_3}) \geq MAX(y_{t_2}, y_{b_1}) \qquad (40)$$

$$(y_2 - \tfrac{1}{2}y_{h_2}) - (y_3 - \tfrac{1}{2}y_{h_3}) \geq MAX(y_{t_3}, y_{b_2}) \qquad (41)$$

$$y_3 - \tfrac{1}{2}y_{h_3} - y_{b_3} \geq 0 \qquad (42)$$

The accessibility will be perfect for module 2 if,

$$x_1 > MAX\ [(x_{w_2} + \tfrac{1}{2}x_{w_1}),\ (\tfrac{1}{2}x_{w_1} + x_{l_1})] \qquad (43A)$$

or

$$x_1 < MIN\ [(x_B - \tfrac{1}{2}x_{w_1} - x_{r_1}),\ (x_B - \tfrac{1}{2}x_{w_1} - x_{w_2})] \qquad (43B)$$

for module 3 if,

$$x_2 > \text{MAX}\left[(x_{w_3} + \tfrac{1}{2}x_{w_2}),\ (\tfrac{1}{2}x_{w_2} + x_{l_2})\right] \quad (44\text{A})$$

or

$$x_2 < \text{MIN}\left[(x_B - \tfrac{1}{2}x_{w_2} - x_{r_2}),\ (x_B - \tfrac{1}{2}x_{w_2} - x_{w_3})\right] \quad (44\text{B})$$

and

$$x_1 > \text{MAX}\left[(x_{w_3} + \tfrac{1}{2}x_{w_1}),\ (\tfrac{1}{2}x_{w_1} + x_{l_1})\right] \quad (45\text{A})$$

or

$$x_1 < \text{MIN}\left[(x_B - \tfrac{1}{2}x_{w_1} - x_{r_1}),\ (x_B - \tfrac{1}{2}x_{w_1} - x_{w_2})\right] \quad (45\text{B})$$

and

$$(y_1 - \tfrac{1}{2}y_{h_1}) - (y_2 + \tfrac{1}{2}y_{h_2}) \geq y_{h_3} \quad (46)$$

or

$$x_1 > \text{MAX}\left[x_{w_3},\ x_{\ 1}\right] + \tfrac{1}{2}x_{w_1} \quad (47\text{A})$$

and

$$x_2 > \text{MAX}\left[x_{w_3},\ x_{\ 1}\right] + \tfrac{1}{2}x_{w_2} \quad (47\text{B})$$

or

$$x_1 < x_B - \tfrac{1}{2}x_{w_1} - \text{MAX}\,(x_{r_1},\ x_{w_3}) \quad (48\text{A})$$

and

$$x_2 < x_B - \tfrac{1}{2}x_{w_2} - \text{MAX}\,(x_{r_2},\ x_{w_3}) \quad (48\text{B})$$

The optimisation procedure is derived easily from the relations above.

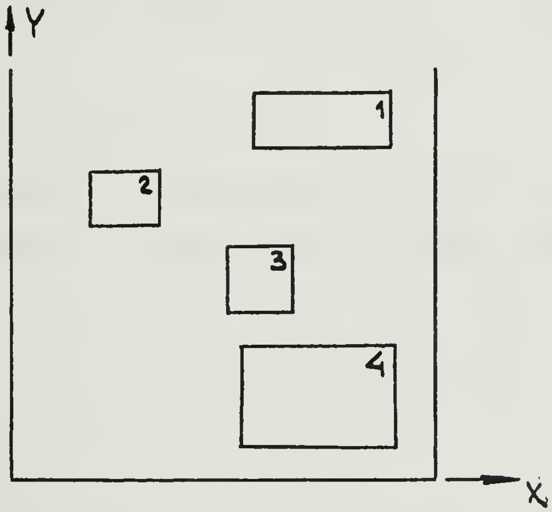
--Determine F_{acces} with (43) to (48).

--If $F_{acces} = 0$, the configuration is found by (36) to (42) and (46) to (48).

--If $F_{acces} \neq 0$, interchange modules after checking the constraints (by interchanging indices) whether the interchange is allowed or not. Determine for all new configurations F'_{acces} and retain the lowest F'_{acces} value by using the relations (43) to (48) with interchanged indices. Stop search when $F'_{acces} = 0$.

NOTE: The number of configurations to be tested is $3! = 6$.

Two-Dimensional Case With n Modules (A)



$y_1 > y_2 > y_3 > \text{-----}> y_n$

Figure 6

The configuration is determined by the constraints in the x-direction:

$$\tfrac{1}{2}x_{w_1} + x_{l_1} < x_1 < x_B - \tfrac{1}{2}x_{w_1} - x_{r_1}$$

$$\tfrac{1}{2}x_{w_2} + x_{l_2} < x_2 < x_B - \tfrac{1}{2}x_{w_2} - x_{r_2}$$

$$\tfrac{1}{2}x_{w_h} + x_{l_n} < x_n < x_B - \tfrac{1}{2}x_{w_h} - x_{r_h}$$

in the y-direction:

$$y_1 \leq y_D - \tfrac{1}{2}y_{h_1} - y_{t_1}$$

$$y_1 \geq \mathrm{MAX}\ (y_{t_2}, y_{b_1}) + \tfrac{1}{2}y_{h_1} + y_2 - \tfrac{1}{2}y_{h_1}$$

$$y_2 \geq \mathrm{MAX}\ (y_{t_3}, y_{b_2}) + \tfrac{1}{2}y_{h_2} + y_3 - \tfrac{1}{2}y_{h_3}$$

$$y_{h-1} \geq \mathrm{MAX}\ (y_{t_h}, y_{b_{n-1}}) + \tfrac{1}{2}y_{h_{n-1}} + y_n - \tfrac{1}{2}y_{h_n}$$

$$y_n \geq \tfrac{1}{2}y_{h_n} + y_{b_n}$$

Total number of constraints is (2n + 2).

Perfect accessibility exists, when in x-direction

$$x_B - \mathrm{MAX}\ [(x_{r_1} + x_{l_1}), x_{w_2}, x_{w_3}, ---, x_{w_n}] - x_{w_1} \geq 0$$

$$x_B - \mathrm{MAX}\ [(x_{r_2} + x_{l_2}), x_{w_2}, ---, x_{w_{n-1}}] - x_{w_2} \geq 0$$

$$x_B - \mathrm{MAX}\ [(x_{r_{n-1}} + x_{l_{n-1}}), x_{w_n}] - x_{w_{n-1}} \geq 0$$

and in y-direction

$$(y_1 - \tfrac{1}{2}y_{h_1}) - (y_2 + \tfrac{1}{2}y_{h_2}) \geq \text{MAX}\,[y_{h_3}, y_{h_4}, ---, y_{h_n}]$$

$$(y_2 - \tfrac{1}{2}y_{h_2}) - (y_3 + \tfrac{1}{2}y_{h_3}) \geq \text{MAX}\,[y_{h_4}, y_{h_5}, ---, y_{h_n}]$$

$$(y_{n-2} - \tfrac{1}{2}y_{n-2}) - (y_{n-1} + \tfrac{1}{2}y_{n-1}) \geq \text{MAX}\,[y_{h_{n-1}}, y_{h_n}]$$

$$(y_{n-1} - \tfrac{1}{2}y_{n-1}) - (y_3 + \tfrac{1}{2}y_{h_3}) \geq y_n$$

If one or more of the conditions in the y-direction is not satisfied, each of the nonsatisfied inequalities

$$(y_i - \tfrac{1}{2}y_{h_i}) - (y_{i+1} + \tfrac{1}{2}y_{h_{i+1}}) \geq$$

$$\text{MAX}\,[y_{h_{i+2}}, y_{h_{i+3}}, -----, y_{h_j}, ----, y_{h_k}, ----, y_{h_n}] \quad (49)$$

for $i < j < k < n$

can be substituted by

$$x_i > \text{MAX}\,[x_{w_j}, x_{w_k}, x_{1_i}] + \tfrac{1}{2}x_{w_i} \qquad (50A)$$

and

$$x_{i\,1} > \text{MAX}\,[x_{w_j}, x_{w_k}, x_{1_{i+1}}] + \tfrac{1}{2}x_{w_{i\,1}} \qquad (50B)$$

or

$$x_i < x_B - \tfrac{1}{2}x_{w_i} - \text{MAX}\,[x_{r_i}, x_{w_j}, x_{w_k}] \qquad (51A)$$

and

$$x_{i\,1} < x_B - \tfrac{1}{2}x_{w_{i\,1}} - \text{MAX}\,[x_{r_{i+1}}, x_{w_j}, x_{w_k}] \qquad (51B)$$

The following crossterms of the objective function do exist if the relationships below are true.

for $i = j+1$

$$\lambda_i T_j \text{ ---- } x_B - \text{MAX}\,[(x_{r_j} + x_{\;\,j}),\, x_{w_j}] - x_{w_j} < 0 \qquad (52)$$

where $i = 2, 3, \ldots\ldots, n$

$j = 1, 2, 3, \ldots\ldots, n-1$

for $i > j+1$

$$\lambda_i T_j \text{ ---- } \underline{A} \quad x_B - \text{MAX}\,[(x_{r_j} + x_{\;\,j}),\, x_{w_j}] - x_{w_j} < 0 \qquad (53)$$

$$\underline{B} \quad (y_j - \tfrac{1}{2}y_{h_j}) - (y_{j+1} + \tfrac{1}{2}y_{h_{j+1}}) < y_{h_i} \qquad (54)$$

and

$$\begin{aligned} x_j &< \text{MAX}[x_{w_i}, x_{l_j}] + \tfrac{1}{2}x_{w_j} \\ x_{j+1} &< \text{MAX}[x_{w_i}, x_{l_{j+1}}] + \tfrac{1}{2}x_{w_{j+1}} \end{aligned} \qquad (55)$$

or

$$\begin{aligned} x_j &> x_B - \tfrac{1}{2}x_{w_j} - \text{MAX}[x_{r_j}, x_{w_i}] \\ x_{j+1} &> x_B - \tfrac{1}{2}x_{w_{j+1}} - \text{MAX}[x_{r_{j+1}}, x_{w_i}] \end{aligned} \qquad (56)$$

$\underline{C}$ For each pair of existing cross-terms in (52), $\lambda_m T_j$ and $\lambda_i T_m$ for $j < m < i$. (57)

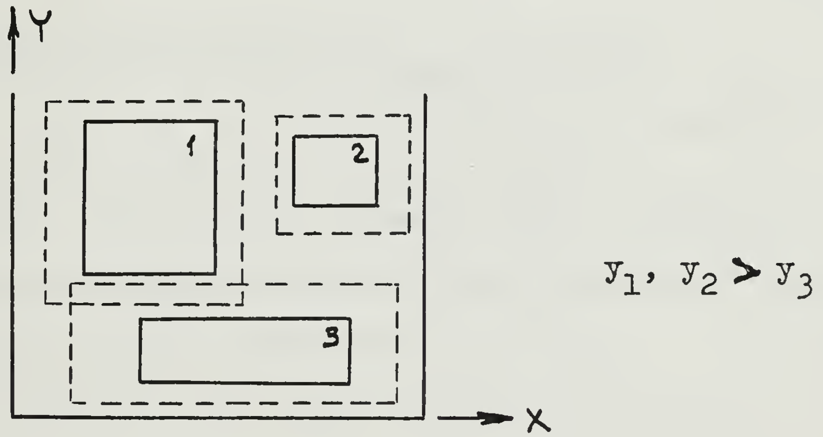
The search for the configuration that belongs to a minimum of the objective function will now be described.

1. Determine the value of F_{acces} by means of the relationships, (52) to (57). If $F_{acces} = 0$, the configuration is fixed by the constraints and (52) to (56) if applicable.

2. If $F_{acces} \neq 0$ in 1., retain its value, make all allowed module interchanges and determine F'_{acces} by interchanging indices in (52) to (57). Retain the lowest F'_{acces}. If $F'_{acces} = 0$, stop interchanging and configuration is determined by the original constraints and (52) to (56) if applicable. Whether an interchange is allowed or not is determined by the geometrical constraints again with interchanged indices.

NOTE: Maximum number of interchanges amounts to $n!$.

<u>Two-Dimensional Case With Three Module Blocs</u> (B)



<u>Figure 7</u>

The configuration is determined by:

$$x_1 \leq x_B - \tfrac{1}{2}x_{w_1} - x_{r_1} \tag{58A}$$

$$x_1 > x_2 + \tfrac{1}{2}x_{w_2} + \text{MAX}\,[x_{l_1}, x_{r_2}] \tag{58B}$$

$$x_2 < x_1 - \tfrac{1}{2}x_{w_1} - \text{MAX}\,[x_{l_1}, x_{r_2}] \tag{59A}$$

$$x_2 > x_{\ 2} + \tfrac{1}{2}x_{w_2} \tag{59B}$$

$$y_1 < y_D - \tfrac{1}{2}y_{h_1} - y_{t_1} \tag{60A}$$

$$y_1 > \text{MAX}\,[y_{b_1}, y_{t_3}] + y_3 + \tfrac{1}{2}y_{h_3} \tag{60B}$$

$$y_2 < y_D - \tfrac{1}{2}y_{h_2} - y_{t_2} \tag{61A}$$

$$y_2 > \text{MAX}\,[y_{b_2}, y_{t_3}] + y_3 + \tfrac{1}{2}y_{h_3} \tag{61B}$$

Accessibility will be ideal ($F_{acces} = 0$) if

$$x_{w_3} + x_{w_1} + x_{w_2} + \text{MAX}\,[x_{r_2}, x_{l_1}] < x_B$$

which is the condition for "free" access of module B.

The following crossterms of the objective function do exist if the relationships below are true.

$$\lambda\,{}_3T_1 \longleftrightarrow \underline{A} \quad x_B - (x_2 + \tfrac{1}{2}x_{w_2}) > x_{w_3} \tag{63}$$

$\underline{B}$ $x_B - (x_2 + \frac{1}{2}x_{w_2}) < x_{w_3}$ (64A)

and

$x_B - (x_2 + \frac{1}{2}x_{w_2}) < x_{w_3}$ (64B)

$\lambda_3 T_2$ ◄--► $\underline{A}$ $x_1 - \frac{1}{2}x_{w_1} > x_{w_3}$ (65)

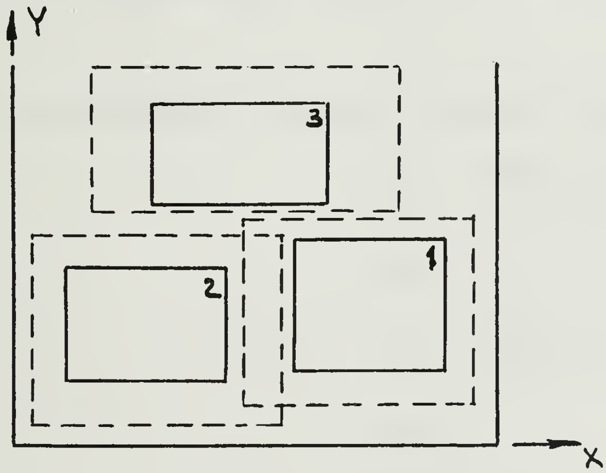
$\underline{B}$ $x_B - (x_2 + \frac{1}{2}x_{w_2}) < x_{w_3}$ (66A)

and

$x_B - \frac{1}{2}x_w > x_{w_3}$ (66B)

Search algorithm for optimal module configuration with respect to the accessibility is similar to case before, except that the configurations are determined by the relations (58) to (66).

The Two-Dominsional Case with Three Modules (C)



$y_3 > y_2, y_1$

Figure 8

The configuration is determined by

$$0 < x_3 < x_B \tag{67}$$

$$x_2 < x_1 - \tfrac{1}{2}x_{w_1} - \text{MAX}\,[x_{l_1}, x_{r_2}] \tag{68A}$$

$$x_2 > x_{\;2} + \tfrac{1}{2}x_{w_2} \tag{68B}$$

$$x_1 < x_B - \tfrac{1}{2}x_{w_1} - x_{r_1} \tag{69}$$

$$y_3 < y_D - y_{t_3} - \tfrac{1}{2}y_{h_3} \tag{70}$$

$$y_2 < y_3 - (\tfrac{1}{2}y_{h_3} + \tfrac{1}{2}y_{h_2} + \text{MAX}[y_{b_3}, y_{t_2}]) \tag{71A}$$

$$y_2 > \tfrac{1}{2}y_{h_2} + \tfrac{1}{2}y_{b_2} \tag{71B}$$

$$y_1 < y_3 - (\tfrac{1}{2}y_{h_3} + \tfrac{1}{2}y_{h_1} + \text{MAX}[y_{b_3}, y_{t_2}]) \tag{72A}$$

$$y_1 > \tfrac{1}{2}y_{h_3} + \tfrac{1}{2}y_{b_3} \tag{72B}$$

Free accessibility for the modules 1 and 2 exists if

$$\underline{A} \quad x_3 - \tfrac{1}{2}x_{w_3} > x_{w_3} \tag{73A}$$

and

$$x_3 - \tfrac{1}{2}x_{w_3} > x_{w_1} \tag{73B}$$

and

$$x_B - x_3 + \tfrac{1}{2}x_{w_3} > x_{w_2} \tag{74A}$$

and

$$x_B - x_3 + \tfrac{1}{2}x_{w_3} > x_{w_1} \tag{74B}$$

or

$$\underline{B} \quad x_3 - \tfrac{1}{2}x_{w_3} > \mathrm{MAX}\,[x_{w_1}, x_{w_2}] \quad (75)$$

and

$$(y_3 - \tfrac{1}{2}y_{h_3}) - (y_2 + \tfrac{1}{2}y_{h_2}) > y_{h_1} \quad (76A)$$

or

$$(x_3 - \tfrac{1}{2}x_{w_3}) - (x_2 + \tfrac{1}{2}x_{w_2}) > x_{h_1} \quad (76B)$$

or

$$\underline{C} \quad x_B - x_3 + \tfrac{1}{2}x_{w_3} > \mathrm{MAX}\,[x_{w_2}, x_{w_1}] \quad (77)$$

and

$$(y_3 - \tfrac{1}{2}y_{h_3}) - (y_1 + \tfrac{1}{2}y_{h_1}) > y_{h_2} \quad (78A)$$

or

$$(x_3 - \tfrac{1}{2}x_{w_3}) - (x_1 + \tfrac{1}{2}x_{w_1}) > x_{h_2} \quad (78B)$$

or

$$\underline{D} \quad x_3 - \tfrac{1}{2}x_{w_3} > x_{w_2} \quad (79)$$

and

$$x_3 - x_3 \quad \tfrac{1}{2}x_w > x_{w_1} \quad (80)$$

Hence if none of the four conditions, A to D, is met $F_{acces} \neq 0$.

The following relationships easily obtainable from the figure, govern the existence of the objective function crossterms stated below:

$\lambda_1 T_3 \longleftrightarrow$ 1. $x_3 - \frac{1}{2}x_{w_3} < x_{w_1}$ (81)

and

$x_B - x_3 + \frac{1}{2}x_{w_3} < x_{w_1}$ (82)

or

2. $x_B - x_3 + \frac{1}{2}x_{w_3} < x_{w_1}$ (82)

and

$x_3 - \frac{1}{2}x_{w_3} > x_{w_1}$ (73B)

and

$(y_3 - \frac{1}{2}y_{h_3}) - (y_1 + \frac{1}{2}y_{h_1}) > y_{h_2}$ (78A)

or

$(x_3 - \frac{1}{2}x_{w_3}) - (x_1 + \frac{1}{2}x_{w_1}) > x_{h_2}$ (78B)

$\lambda_2 T_3 \longleftrightarrow$ 1. $x_B - x_3 + \frac{1}{2}x_{w_3} < x_{w_2}$ (83)

and

$x_3 - \frac{1}{2}x_{w_3} < x_{w_3}$ (84)

or

2. $x_3 - \frac{1}{2}x_{w_3} < x_{w_3}$ (84)

and

$(y_3 - \frac{1}{2}y_{h_3}) - (y_2 + \frac{1}{2}y_{h_2}) > y_{h_1}$ (76A)

or

$(x_3 - \frac{1}{2}x_{w_3}) - (x_2 + \frac{1}{2}x_{w_2}) > x_{h_1}$ (76B)

$\lambda_2 T_1 \longleftrightarrow$ 3. $x_3 - \frac{1}{2}x_{w_3} > x_{w_3}$ (73A)

and

$(y_3 - \frac{1}{2}y_{h_3}) - (y_1 + \frac{1}{2}y_{h_1}) < y_{h_2}$ (85A)

or

$(x_3 - \frac{1}{2}x_{w_3}) - (x_1 + \frac{1}{2}x_{w_1}) < x_{h_2}$ (85B)

and

$y_3 - \frac{1}{2}y_{h_3} - y_{h_1} > y_{h_2}$ (86)

or

$x_B - x_1 > x_3 + x_{w_2}$ (87)

or

$x_B - x_3' + \frac{1}{2}x_{w_3} > x_{w_1}$ (74B)

$\lambda_1 T_2 \longleftrightarrow$ 1. $(y_3 - \frac{1}{2}y_{h_3}) - (y_1 + \frac{1}{2}y_{h_1}) < y_{h_2}$ (85A)

or

$(x_3 - \frac{1}{2}x_{w_3}) - (x_1 + \frac{1}{2}x_{w_1}) < x_{h_2}$ (85B)

and

$x_3 - \frac{1}{2}x_{w_3} > x_{w_1}$ (73B)

and

$y_3 - \frac{1}{2}y_{h_3} - y_{h_2} > y_{h_1}$ (88)

or

$x_3 - \frac{1}{2}x_{w_3} > x_2 + \frac{1}{2}x_{w_1}$ (89)

or

$$x_3 - \tfrac{1}{2}x_{w_3} > x_{w_2} \tag{73A}$$

The terms $\lambda_1 T_2$ and $\lambda_2 T_1$ are considered in connection with the cases in which the modules 1 and 2 are, if the constraints allow it, just displaced and NOT removed from the system in order to provide free passage for the modules 2 and 1 respectively. This situation is most common in marine systems.

The search algorithm for the maximum systems accessibility is the same as for the cases investigated before.

The General Case of n Blocs in Three Dimensions

The two-dimensional cases investigated in the last sections do show the extreme complexity of accessibility optimisation, but do give us also an analogous way of approaching the accessibility in the case with n blocs without going into detail.

1. Determine the geometrical constraints of the initial configuration analogous to the 2- and 3-bloc cases.

2. Determine the value of the accessibility function for the initial configuration by listing of all possible $\lambda_i T_j$'s in relation to the geometry of the configuration analogous to the 2- and 3-module cases before.

3. If $F_{acces} = 0$, use constraints of 1. and 2. to find the configuration.

4. If $F_{acces} \neq 0$, make all allowed module interchanges, and choose configuration with lowest F_{acces}. As soon as $F_{acces} = 0$, the absolute optimum is reached. Stop searching.

As we have seen for the extremely simple cases of three blocs, the number of relations to be set up for each configuration is considerable. In a marine system a number of 15 to 20 modules is certainly not uncommon.

Now the maximum number of interchanges in the described procedure for obtaining all possible geometrical combinations with their quantitative accessibility is huge. For the

extremely moderate case of 20 modules this means already a maximum number of $20! = (2.43)(10)^{18}$ different configurations to analyse. This number makes the search for an absolute accessibility maximum completely impractical, with the exception of cases with few modules. A partial solution will be considered in the next section.

Algorithm for Suboptimal Allocation

As was observed in the last section, it is not feasible with present means of computation to find the optimal configuration with respect to the accessibility, as a consequence of the huge number of cases to be analysed.

In order to increase the accessibility however, of the initial configuration a computer-aided sub-optimum solution will be obtained using the algorithm below, which was originally developed by Gere and described by Glaser [6] for the suboptimisation of cable lengths between electronic system components.

1. Rank the modules in the system from 1 to n. Determine the value of F_{acces} of the initial configuration as before. If $F_{acces} = 0$, the initial arrangement is optimal.

2. If $F_{acces} \not< 0$, and no configuration constraints are violated, temporarily interchange module 1 and 2. Determine F'_{acces}. If $F'_{acces} < F_{acces}$, retain F'_{acces} and if $F'_{acces} \neq 0$, restore 1 and 2 in their original locations. Consecutively interchange 1 and 3, 1 and 4, etc. in the same way and under the same conditions as the modules 1 and 2. Record only largest improvement with its configuration.

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2. If $F_{acces} \neq 0$, and no configuration constraints are violated, temporarily interchange module 1 and 2. Determine F'_{acces}. If $F'_{acces} < F_{acces}$, retain F'_{acces} and if $F'_{acces} \neq 0$, restore 1 and 2 in their original locations. Consecutively interchange 1 and 3, 1 and 4, etc. in the same way and under the same conditions as the modules 1 and 2. Record only largest improvement with its configuration.

3. If largest improvement under 2. is positive, make that interchange, which leads to that largest improvement, permanent.

4. Repeat process of 2. and 3. with module 2, except that module 2 is NOT interchanged with module 1. Consecutively, make interchanges with module 3, with the positions of 1 and 2 fixed, and so on up to the last module n.

5. Repeat process 2, 3, and 4 as long as improvements do result or a sufficient criterium is satisfied.

Due to the stated condition in the algorithm, that an improvement must have been made before a module is interchanged permanently, it follows that the initial value of F_{acces} is reduced. The total reduction is the sum of the improvements generated by each permanent interchange.

The maximum number of interchanges (changing two at a time) is C_2^n, which means for 20 modules, 190 interchanges and which is feasible for computer-aided allocation. See the flow chart in Appendix A.

Discussion of the Result

1. The result obtained in the last section enables us to increase the accessibility with respect to objective function derived in an earlier chapter.

2. The method will not lead to the absolute optimum in most cases, but to a suboptimum, depending on the initial module arrangement. Different initial configurations will lead to different final configurations with different accessibilities. The computer-aided "light pen" method will be extremely useful in the process of the generation of "new" arrangements.

3. The solution method is certainly advantageous compared to the few configurations that can be studied presently by making some manual interchanges, while reliability and replacement times are not or perhaps only intuitively taken into account.

4. The given method is not implemented, and will require a considerable effort due to the complexity of the problem which was already shown for the simple cases.

5. To avoid a cumbersome generation of the initial configuration, a random initial allocation method might be considered similar to the one used by Glaser.

6. The method will be applicable for more complicated forms than just box-shaped modules. Complicated forms may be built up using the box-shaped forms, while adjusting the interchange procedure as well as the relative geometrical constraints.

CONCLUSIONS

In addition to the more specific conclusions made before, the following general conclusions can be drawn.

1. It is possible to express the accessibility of a given volume constrained system with one single access opening quantitatively in terms of the reliability and maintainibility characteristics of the system components for the case of the replacement of a single failed module.

2. Module allocation for system design purposes with respect to the optimisation of the accessibility is in principle possible using a combination procedure and the derived objective function for the accessibility.

3. A pure analytical method was not available for the accessibility optimisation.

4. No feasible design procedure exists to arrange any arbitrary number of modules in such a way that an absolute minimum of the accessibility objective function is reached.

5. A computer aided algorithm can assist with the rearrangement of a given module configuration in such a way that its accessibility is increased and a suboptimal configuration is obtained.

6. The supply of reliable failure rates and mean time to replace data for all subsystems is an absolute requirement for the investigation of a system's accessibility.

7. The accessibility and its related loss for the operation of the system can be obtained as functions of the available volume and shape of the permanent boundary, e.g., engineroom volume vs. payload volume of a volume limited ship.

RECOMMENDATIONS

1. The given module allocation algorithm should be implemented for the accessibility suboptimisation of the general case with n modules in three dimensions starting from a given configuration.

2. The accessibility with respect to unscheduled downtime should be weighted with the accessibility required for preventive maintenance and hence related to the replacement of more than one module at a time.

3. The development of a computer aided "on-line" design method, using the accessibility suboptimisation, should be considered. The advantage of such an allocation method is that we do not depend on just one starting configuration, but that many configurations can be tried out within a reasonable amount of time and hence an increased probability of a better suboptimum.

4. The allocation of piping and wiring should be investigated in connection with the module allocation. Total suboptimisation with respect to piping and wiring costs as well as the costs for module accessibility seems to be feasible when interchanging the modules during the rearrangement procedure.

[illegible]

[illegible]

5. A study of accessibility improvement for the case of more than one single access opening and specifically access through the semi-permanent boundary, e.g., removal of modules from the engineroom through a temporary hole cut in the shell of a ship.

6. A study of the optimum arrangement, when spare modules are carried within the systems permanent boundary.

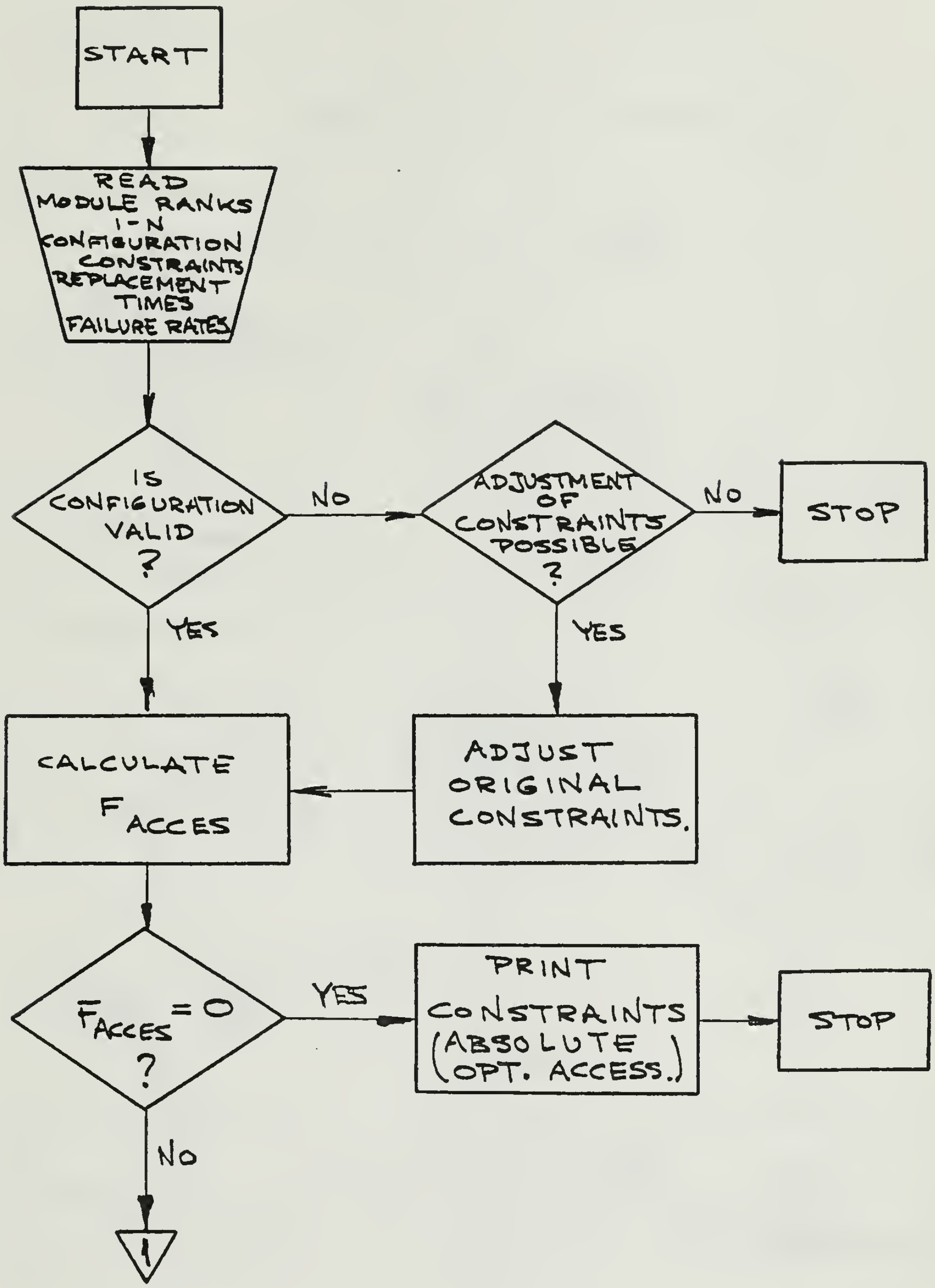
APPENDIX A

FLOWCHART

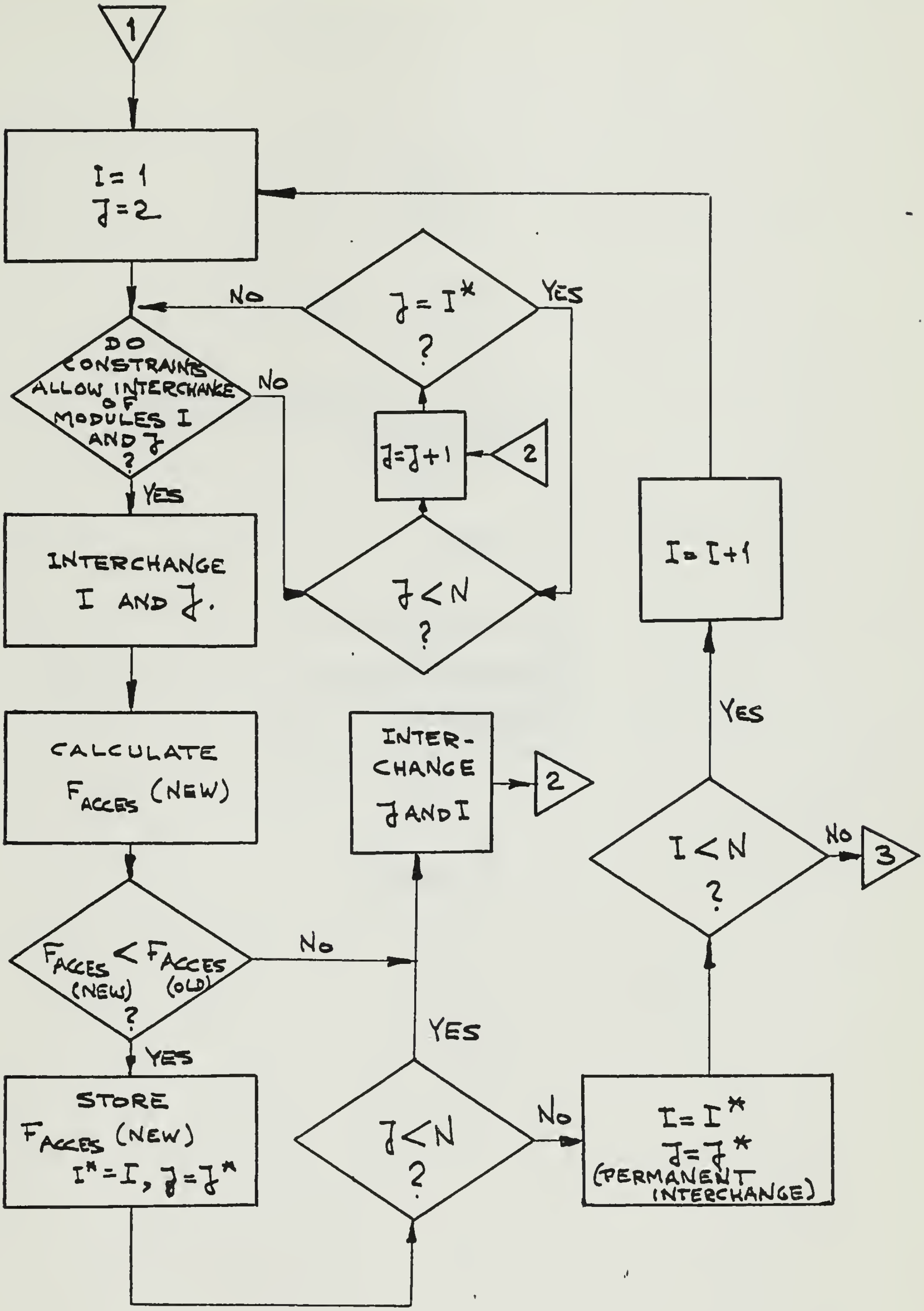
Accessibility Optimisation Algorithm

FLOWCHART

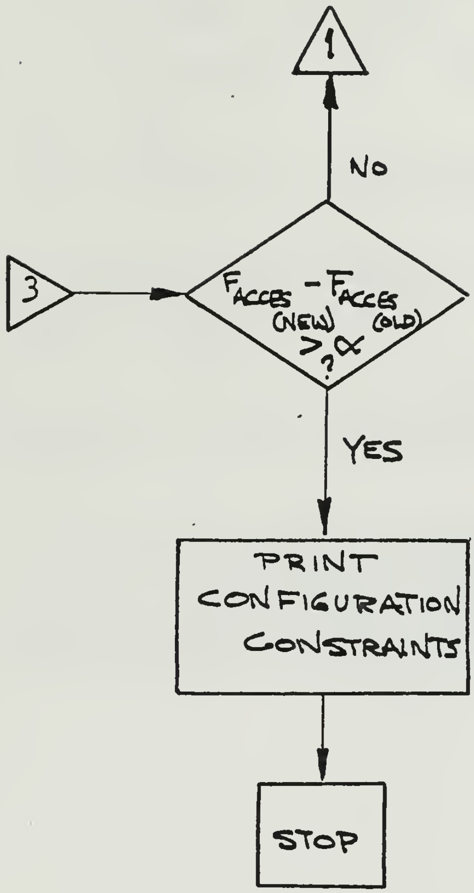
Accessibility Optimisation Algorithm



FLOWCHART (continued)



FLOWCHART (continued)



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